Subject: Changes to Kalman-filter processor for the C-130
Al Cooper
8 July 2019

Background

The Kalman-filter processor was developed and tested for the GV, as documented in Cooper [2017]. The basic structure will work for the C-130 also, but a few adaptations will improve performance when applied to that platform. This memo documents the changes that have been made and might be needed in the future.

Original Processing Code

The code for the Kalman processor is included with the ".Rnw" file that generated the NCAR Technical Note, and it can be found at this GitHub repository. Complete files needed to reproduce the report are contained in this ZIP file, which includes a "Workflow" description with additional information regarding reproducibility. This memo is an addition to that Workflow document describing how the processor has been modified to process C-130 data files.

A separate processor, named "KalmanFilter.R," was constructed to duplicate the code in the Technical Note but to run as an independent R script to process selected files. The modifications here have been made to that processor rather than to the ".Rnw" file that generated the NCAR Tech Note in order to leave that .Rnw file consistent with the file available on OpenSky. "KalmanFilter.R" shares key processing "chunks" with the original processor, but some have had to be modified to adapt them to the C-130.

Changes

Some changes are trivial:

1. The distance from the IRU to the GPS antenna is different on the C-130 vs the GV so a branch has been added that selects the right distance based on the "Platform" attribute in the netCDF file.

2. Line 122 in chunks/Kalman-setup.R was changed by the addition of "as.numeric()" surrounding the right side of the assignment statement. Some change in R apparently required this, because the assignment statement that previously was working started to produce an error that prevented the processor from running.

Other changes are needed to address possible differences between the IRUs on the two platforms. Similar changes might also be needed for the GV if the reference IRU is changed. The changes were as follows:

Component	c_0 [m s^{-2}]	c_1
BLONGA	0.0014	1.0017
BLATA	-0.0062	1.0744
BNORMA	-0.0149	1.0141

Table 1: Calibration results for accelerations in the *a*-frame.

1. *Calibration coefficients.* For the GV, the performance of the Kalman filter was improved if "calibration factors" were applied to the measured accelerations (BLATA, BLONGA, BNORMA).[1] These calibration factors for the GV were listed in Table 2 of the Tech Note, and these are applied during Kalman-filter processing, but it is useful to determine replacements for use with the C-130. The procedure for finding these calibrations is to differentiate the GPS-provided measurements of velocity to find the acceleration vector in the *l*-frame (with local E-N-up components), then transform to the *a*-frame where the body accelerations are measured. Corrections are necessary for the Coriolis components of the acceleration. The three components of the acceleration then can be compared to determine if an adjustment is warranted. Code for this comparison is included in this processing file, and an example of the comparison after calibration is shown in Fig. 1. The calibration coefficients determined in this way are listed in Table 1. The result for the lateral accelerations (BLATA) is less constrained than the others because lateral accelerations are an order of magnitude smaller than longitudinal or normal accelerations, so this calibration result will not be used, but the others will be applied in the following processing.[2]

2. *Time shifts.* The relative timing between the variables recorded from the IRU and those produced by the GPS affects the performance of the Kalman filter. For example, if there is a lag between these data sources during a turn, that lag will appear as a difference between the two measurements. It is useful to remove the apparent lag before running the Kalman filter. There are two effective ways that the lag can be estimated:

    (a) From pitch maneuvers. The lag between the measurement of pitch from the INS and the measurement of rate-of-climb from the GPS affects the extent to which induced rate-of-climb can be eliminated from the measured vertical wind during the maneuver. QAtools provides a convenient way to analyze pitch maneuvers to minimize the transmitted fraction of the induced aircraft motion. For example, WECAN test flight #2 included a good pitch maneuver (17:55:00 – 18:00:00 UTC) and time shifts can be determined by using the sliders in the QAtools pitch-maneuver display. An imposed pitch delay of 160 ms led to only 0.8% transmission, one of the best pitch-maneuver results observed for the C-130.

[1] It may be the case that such calibrations are applied by the INS internally during its "mechanization" calculations and yet don't appear in the reported accelerations, but I wasn't able to find information to either confirm this or give the calibrations applied.

[2] I did not have a high-rate file available with the body accelerations included. This would best be repeated with such a file.

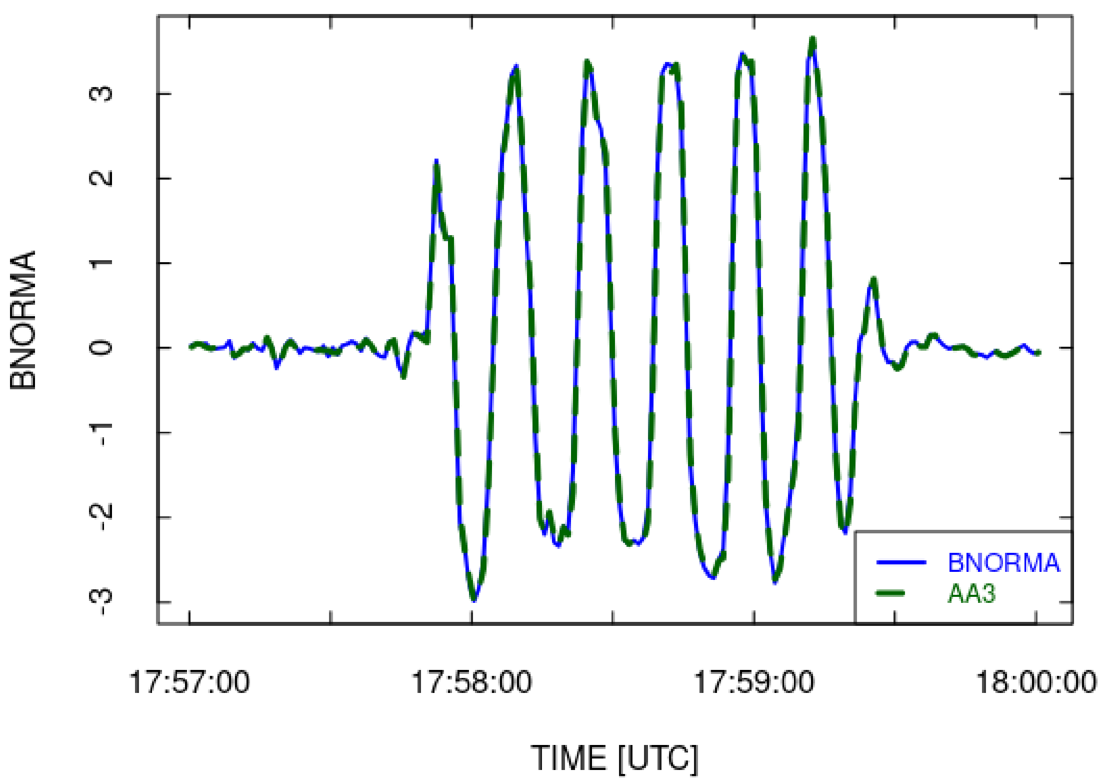

Figure 1: Comparison of the normal acceleration measured by the IRU (BNORMA) and that deduced by differentiating the GPS measurement of aircraft velocity and then taking the normal component after transformation of the acceleration vector to the a-frame, for the period of a pitch maneuver on WECAN test flight 2.

(b) From a circle maneuver if it includes both left and right turns, because as discussed in Cooper et al. [2016] the appropriate time shift can be determined with low uncertainty from such a maneuver. Analysis of the circle maneuver flown on WECAN test flight #2, 18:22:07–18:27:52 UTC, indicates that the appropriate time shift for the heading variable (THDG) is 154 ms. This is in reasonable agreement with the shift deduced from the pitch maneuver.[3]

In the initial processing for this WECAN test flight, the heading "TimeLag" attribute is -80 ms and that for pitch is -40 ms. Other time lags are: LAT and LON, -160; ALT, -40; VEW and VNS, -80; VSPD, -60; ROLL, -40; ACINS, -60. Because corrections are applied for these, the time shift already applied is the negative of the listed time lags. Therefore, if it is desired to have a shift in THDG of 154 ms, an additional shift of 74 ms is needed. The shift determined from the two preceding maneuvers, however, finds the shift needed relative to the GPS measurements of aircraft velocity, not the shift required relative to the data-system time. An equivalent shift would be produced by leaving the $+80$ ms shift in THDG but imposing a new shift of -74 ms on GGVEW, GGVNW, and GGVSPD. This is the approach now taken in "KalmanFilter.R" for the C-130.

3. Some or all of the IRU-produced body accelerations and body rotations may be missing. For example, the current WECAN files have BLATA, BLONGA, and BNORMA but not BPITCHR, BROLLR, and BYAWR, and all six are needed by the Kalman filter. The Tech Note, section 3.2, developed a procedure for reconstructing these from the velocity components and attitude angles from the INS, and here the part of that procedures that pertains to the body rotation rates can be used to reconstruct those missing components.[4] The .Rnw code that produced the Tech Note included a code "chunk" named "AddIRUVariables.R" for this purpose, and that chunk is included in the processor script ("KalmanFilter.R"), but a modification was made to that chunk to skip construction of the body accelerations if they are already present.

4. As processed in May 2019, an offset of $+0.76^\circ$ was imposed on THDG. This will confound the Kalman processor because it needs to know what the IRU produced for heading, without this offset, so any offset should be removed before processing. This also applies to the Ranadu function "CorrectHeading()", but in that case the routine includes code to remove the offset.[5] The result of this function is shown in Fig. 2. For larger or smaller time shifts, the difference between the left and right turn error bars increases.

[3] The processing time lags used for these measurements differ, however: TimeLag=-80 ms for THDG but -40 for PITCH.

[4] Better would be to reprocess in nimbus to add the missing body-rotation variables.

[5] For the C-130 in WECAN, an additional offset of -0.05 appeared useful, as well as a time shift of 90 ms. The latter gave corresponding results for the left and right turns in the CorrectHeading() function. A time lag of -80 ms was used during nimbus processing, so the imposed shift is actually $+170$ ms, not seriously in conflict with the estimate of $+154$ ms obtained from the circle maneuver.

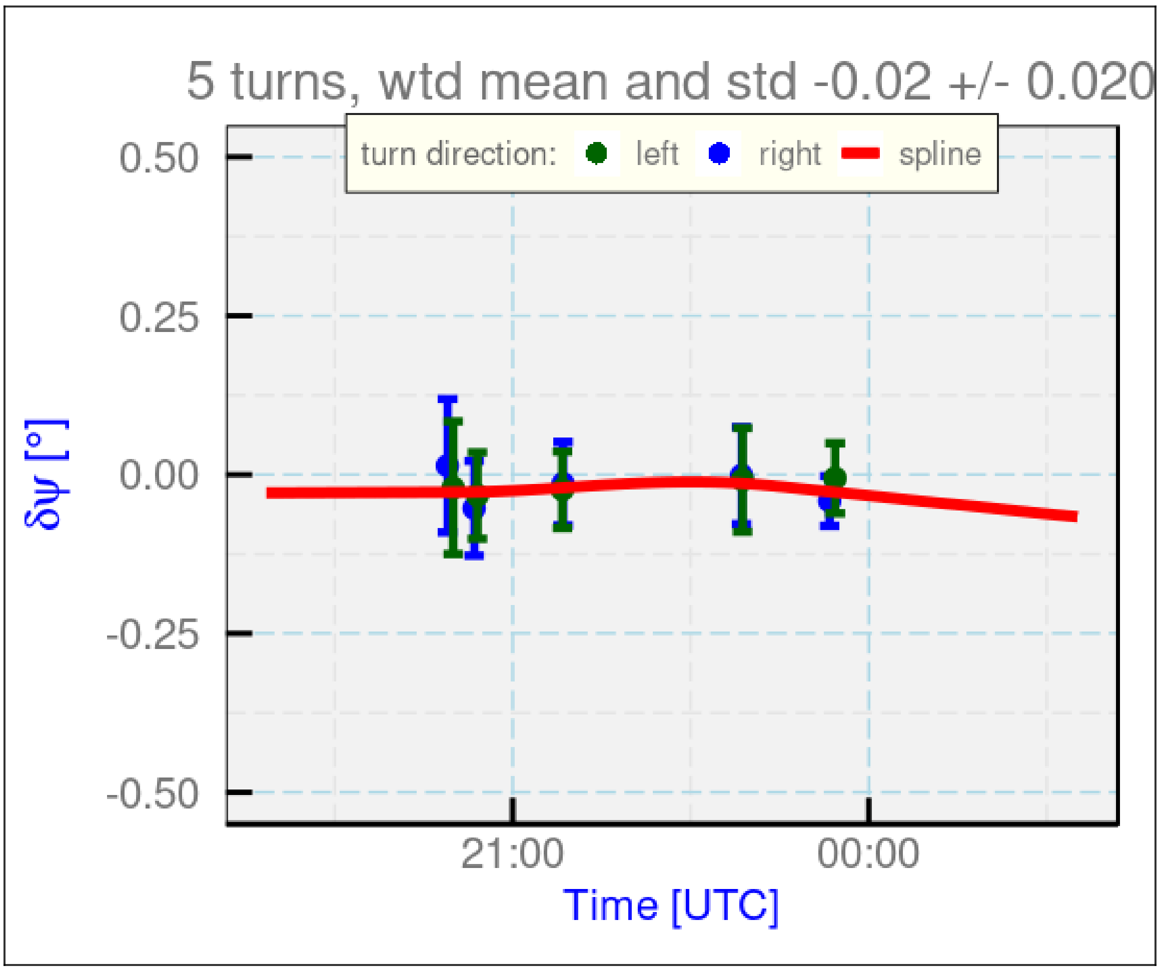

Figure 2: The error in heading as estimated using the Ranadu function "CorrectHeading()", for WECAN research flight 9.

Other Comments:

1. The most difficult adjustment to detect is that to heading. To obtain estimates of the error in heading, it is beneficial to incorporate sources of horizontal acceleration, like turns or pitch maneuvers, into flight plans to ensure that there are frequent periods with horizontal accelerations. This can be done, for example, using $+30$, -60, $+30°$ turns into ferry legs. Course-reversal turns are also effective, and the most effective include turns in both directions to help compensate for the effects of timing errors. The present implementation of the Kalman filter includes special variables to help detect an error in heading, but any Kalman filter will need horizontal accelerations in order to find valid heading corrections. Turns produce horizontal accelerations in the aircraft- relative a-frame, and the INS uses the heading to resolve those accelerations into changes in the Earth-relative components of the aircraft velocity vector. The present implementation of the Kalman filter uses pseudo-observations of those same accelerations obtained by differentiating the GPS-provided components of the aircraft velocity vector, and an error difference then appears as a feedback component to the error in heading. The Ranadu function "CorrectHeading()" also produces an simplified calculation of the offset error, but the Kalman-filter result includes additional sources of possible error and therefore should be a superior result.

2. The plots generated at the end of the "KalmanFilter.R" run show relatively smooth variation in pitch and roll when plotted in the Earth-relative l-frame but much more variability in the a-frame. The reason is that the IRU maintains its virtual stabilized platform in an inertial frame, much closer to the l-frame, so corrections tend to vary slowly there. In the a-frame, every change in flight direction produces a mixing of the pitch and roll corrections, so there are frequent changes in the corrections when calculated in the a-frame (where they must be used to calculate wind).

3. The processor produces a new netCDF file with "KF" appended to the flight name (e.g., WECANrf09KF.nc). That file has new variables with "KF" in the names and an attribute of "KalmanFiltered" == TRUE. Wind measurements are recalculated using revised values of angle-of-attack (if requested), pitch, heading, aircraft motion, etc., and are produced as normal wind (WDKF, WSKF, WIKF) and as horizontal components (UXKF, VYKF). The corrections applied to pitch, heading, and the aircraft ground-speed components are filtered to leave only low-frequency components, to avoid the introduction of noise that might contaminate the high-rate variance spectra.

4. Because the Kalman-filter corrections are only applied after filtering (with characteristic period of 600 or 900 s), it is not useful to run the Kalman filter on high-rate netCDF files. Therefore, if the requested file is high-rate, a 1-Hz version is extracted and the Kalman processor is run on that low-rate file. After determining the corrections, they are applied to the variables in the high-rate file.

5. The "KalmanFilter.R" script includes some options:

(a) "addAK" and "addSS" calculate new values of angle-of-attack and sideslip angle based on the complementary-filter representation of the former and recent calibrations for WECAN (for the C-130). These are used in the subsequent calculation of wind variables.

(b) "simple only" skips the Kalman filter and instead applies the simplified estimates of errors in pitch, roll and heading as obtained from the Ranadu functions "CorrectPitch()" and "CorrectHeading()". Wind calculations are then based on those corrected values.

(c) The "NSTEP" variable defined at the start of the run determines the size of time steps taken by the Kalman filter. A value of 15 or 30 is recommended.

Illustrations of Results

The following plots show some of the corrected measurements:

Horizontal Position

The location of the aircraft is provided by the GPS with low uncertainty, so the Kalman filter does not improve these measurements significantly. Figure 3 shows a comparison of the conventional LATC variable and the new LATKF variable. Both show minor variations relative to the GPS position, with particular excursions during turns, but the variable corrected by the Kalman filter has lower standard deviation from the GPS value (9.6 m for LATKF vs 15.8 m for LATC). GGLAT may still be the best position variable.

Aircraft Groundspeed Components

As for position, the aircraft velocity relative to the Earth is measured well by the GPS, so the Kalman-filter corrections applied to the measurements from the INS are primarily a check on the Kalman filter. The results are shown in Fig. 4. The corrected results (VNSKF) are improved substantially over the uncorrected measurements, but the result is not a significant improvement over the measurement produced by the complementary-filter approach (VNSC, not shown). The strong Schuler oscillation present in the original measurement from the INS is removed effectively by the Kalman filter.

Pitch and Roll

The measurement of pitch can be improved significantly by the Kalman filter because the Schuler oscillation evident in Fig. 4 also produces errors in the pitch that can be corrected by using the error signal in the ground-speed measurements. As explained in "Other Comment" #2, the errors

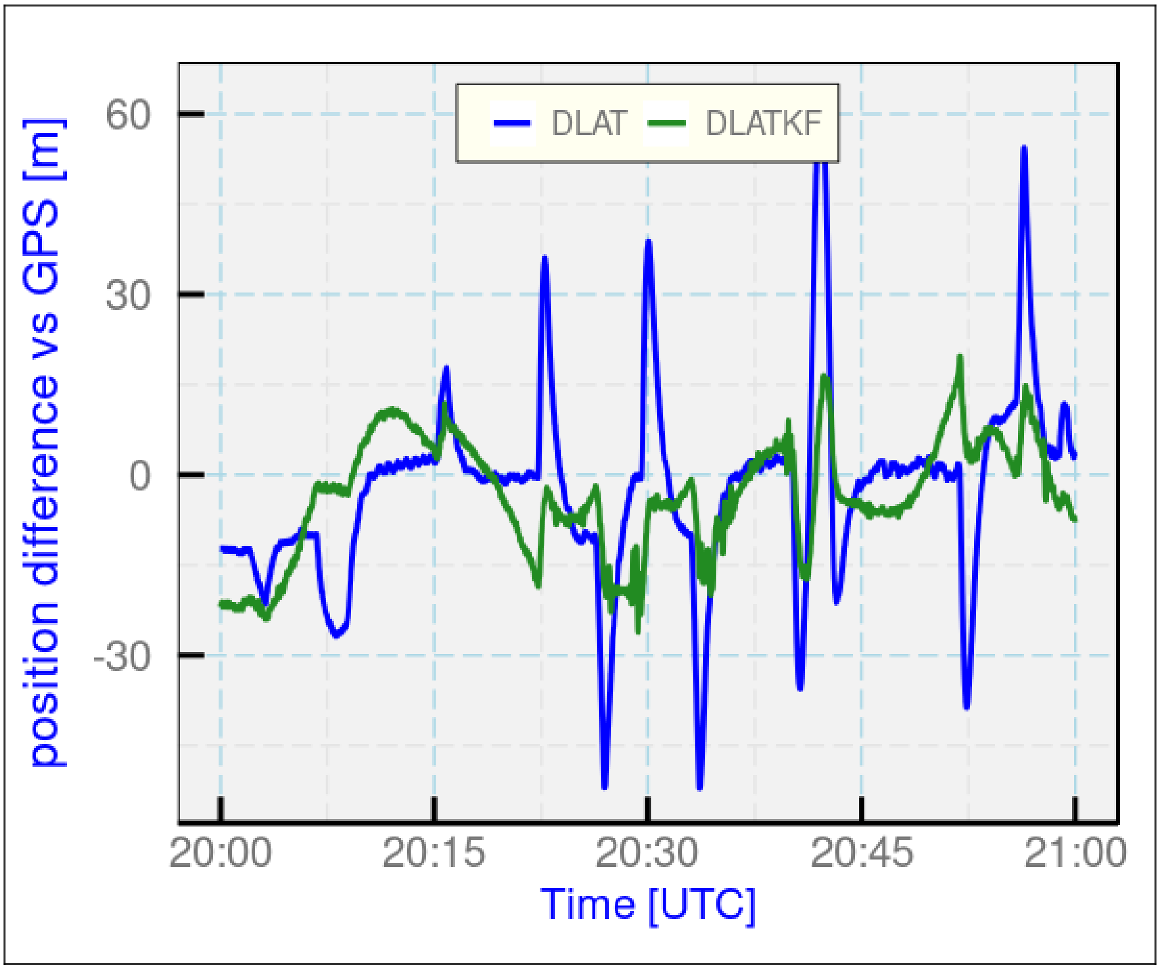

Figure 3: The difference between positions provided by the conventional variables GGLAT and LATC (DLAT) and the difference vs. the new variable LATKF (DLATKF) for a segment of WE-CAN research flight 9. For this plot, the GPS measurement GGLAT was shifted 90 ms later to minimize the differences.

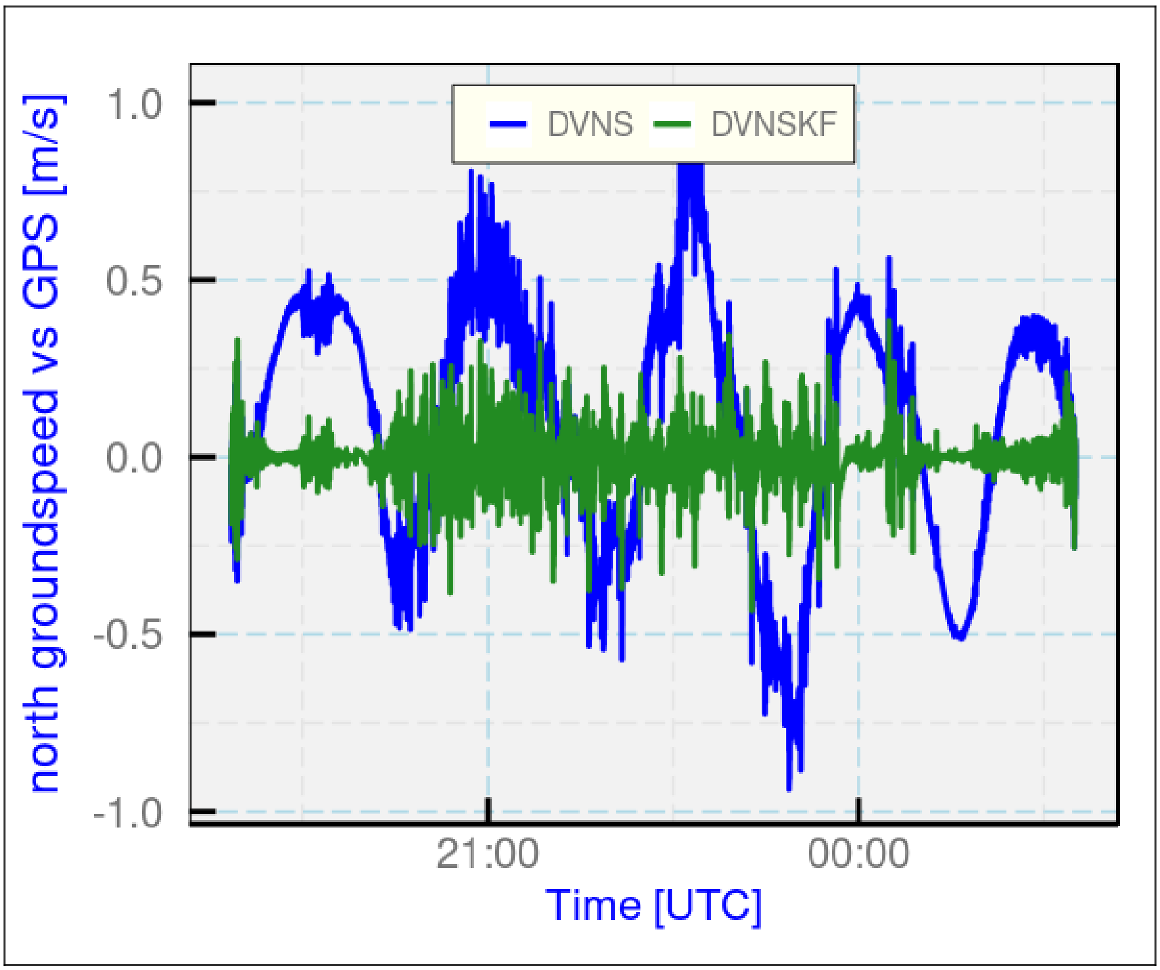

Figure 4: The difference between the northward component of aircraft groundspeed measured by the INS (VNS) and that measured by the GPS (GGVNS), and the corresponding difference for the variable corrected by the Kalman filter (VNSKF).

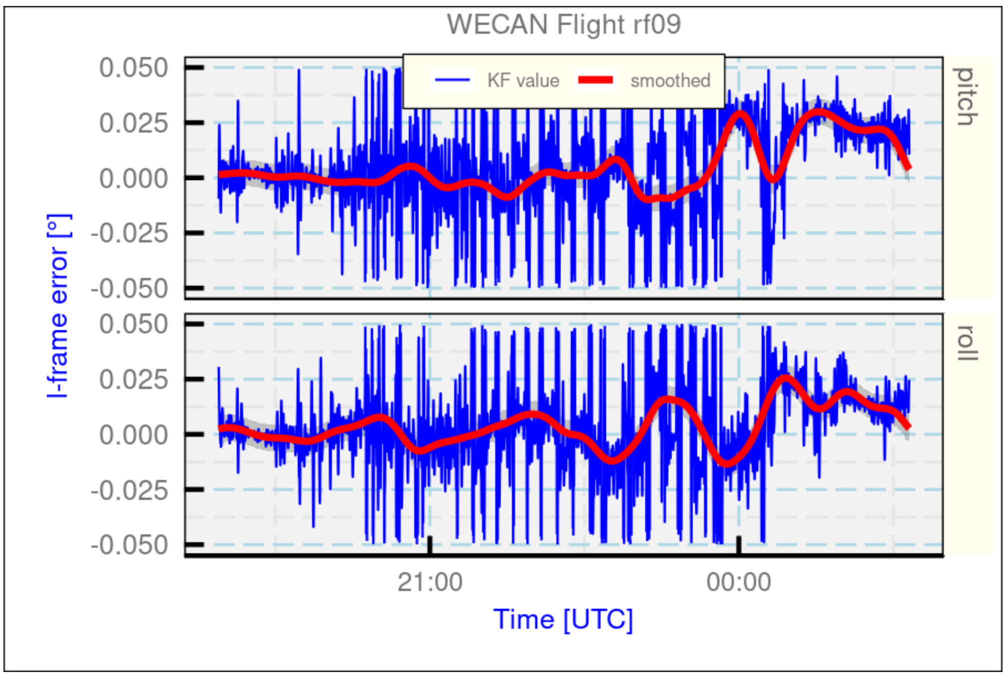

Figure 5: The estimated errors in pitch and roll determined by the Kalman filter. The blue lines are the running Kalman-filter estimates, and the red lines are filtered results used for the actual corrections applied to the measurements. There is a shaded ribbon following the filtered lines that indicates a two-standard-deviation estimate of the uncertainty.

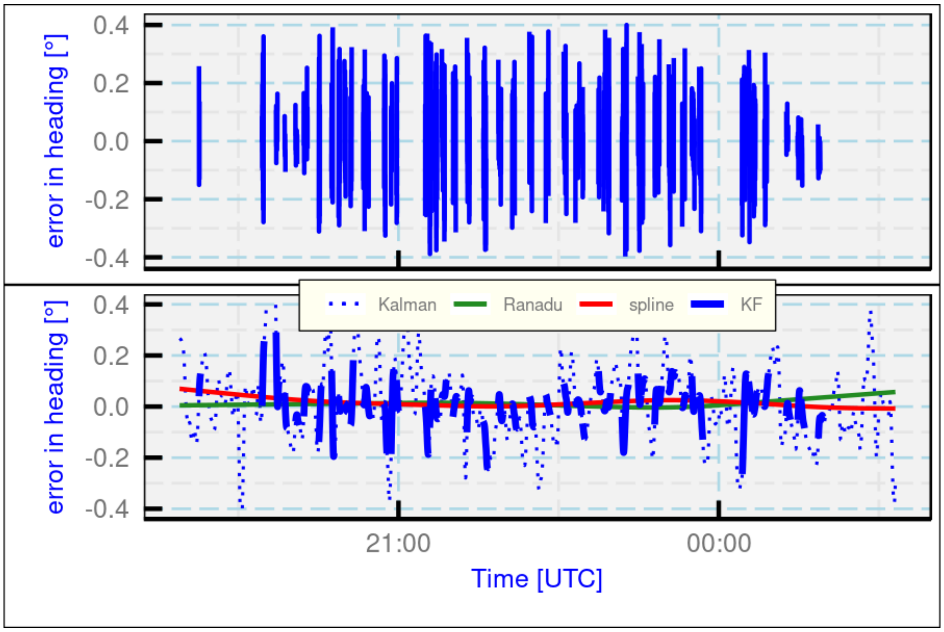

Figure 6: The error estimates for heading. See the text for explanations of the values in these plots. Data from WECAN research flight 9.

in pitch and roll are easier to detect and correct in the Earth-relative l-frame rather than in the a-frame where they are defined by convention. Figure 5 shows the error determined by the Kalman filter for WECAN research flight 9. The corrections are small, mostly smaller than 0.025°, but they correspond to the Schuler oscillation in groundspeed and have uncertainty mostly smaller than 0.01°. For the C-130, a pitch uncertainty of this magnitude corresponds to a typical uncertainty in vertical wind of about 0.02 m/s, so this is an important improvement in the measured wind. To obtain corrected measurements, these l-frame values must be translated to the a-frame, where the results appear more variable but still have the same estimated uncertainty.

Heading

The improvement in heading is dependent on characteristics of the flight pattern, and the results can be quite different for different flights. The best cases include frequent turns, preferably in both directions, to produce the accelerations that constrain the heading. The estimated errors in heading are shown in Fig. 6. The top panel shows the direct error estimates from the Kalman filter, plotted only where the horizontal acceleration is larger than $1\,m\,s^{-2}$ to select only estimates expected to be reliable. The bottom panel shows four results:

1. "Kalman" – The smoothed error estimate from the Kalman filter, with smoothing over about 60 s. The dashed line indicates where the estimated uncertainty in the error is $> 0.02°$.

2. "KF" – Also the smoothed error estimate from the Kalman filter, with smoothing over about 60 s, but plotted as a thick solid blue line to show where the estimated uncertainty is smaller

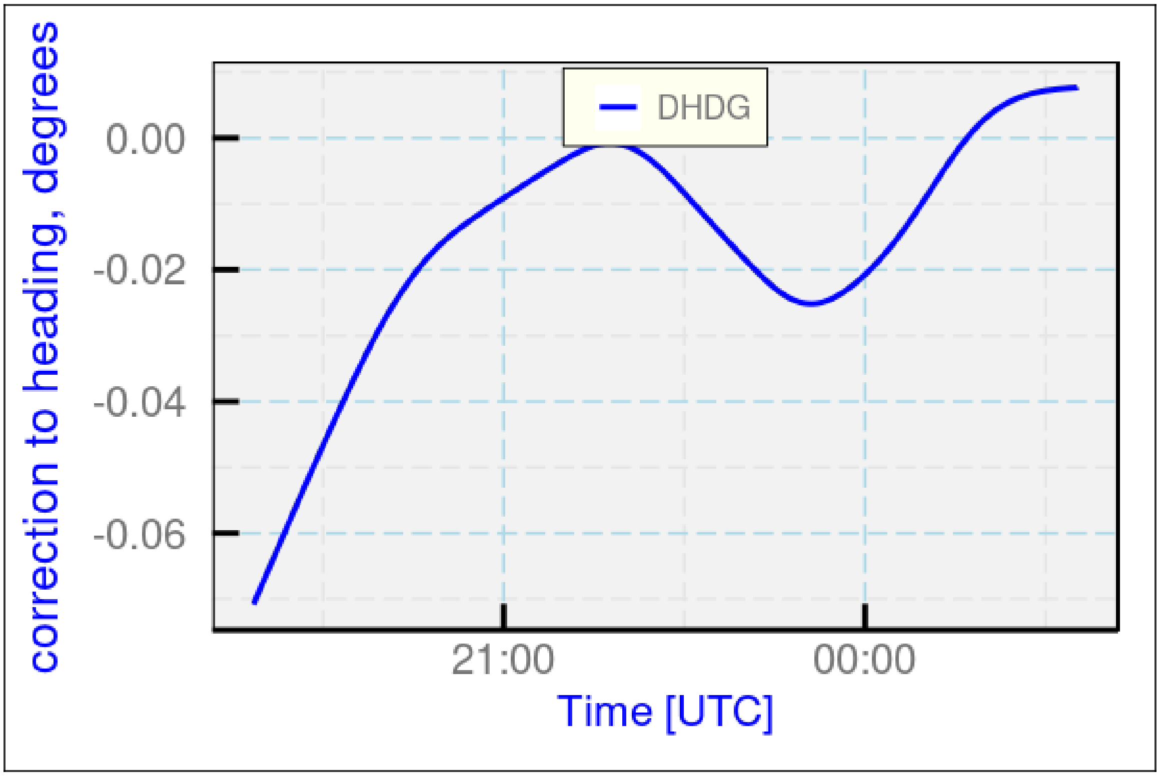

Figure 7: The difference between the heading with Kalman-filter corrections and the original heading (with applied "calibration coefficients" removed), for WECAN research flight 9.

than $0,02°$. This flight incorporates enough regions with significant horizontal accelerations to produce low-uncertainty estimates over much of the flight.

3. “spline” – An estimate based on a spline fit to the error estimate, where the fit takes into account the estimated uncertainty over the time span of the correction. For details, see the code. This is the actual correction applied to the measurements.

4. “Ranadu” – The estimate obtained by the Ranadu function “CorrectHeading()”.

The estimated errors are all small, less than 0.1°everywhere during this flight. A heading error of 0.1° would change the measured lateral component of the horizontal wind by about 0.2 m/s, and the estimated uncertainty in the correction is about 0.02°, so the correction reduces the uncertainty in lateral wind arising from heading to about 0.04 m/s.[6] The difference between the original and corrected heading is shown in Fig. 7.

[6]A problem arises if “calibration coefficients” are used to adjust the heading. Those must be removed during processing by the Kalman filter, but the correction obtained is then applied to the original measurement with the false calibration coefficients. The result will then be in error by the amount of the offset introduced by the calibration coefficients.

Bibliography

W. A. Cooper. A Kalman filter to improve measurements of wind from NSF/NCAR research aircraft. NCAR technical note NCAR/TN-540+STR, Earth Observing Laboratory, NCAR, Boulder, CO, USA, sep 2017. URL http://dx.doi.org/10.5065/D61N7ZTS.

W. A. Cooper, R. B. Friesen, M. Hayman, J. B. Jensen, D. H. Lenschow, P. A. Romashkin, A. J. Schanot, S. M. Spuler, J. L. Stith, and C. Wolff. Characterization of uncertainty in measurements of wind from the NSF/NCAR Gulfstream V research aircraft. NCAR technical note NCAR/TN-528+STR, Earth Observing Laboratory, NCAR, Boulder, CO, USA, jul 2016. URL http://n2t.net/ark:/85065/d7qr4zqr.